

Stirling Cryocooler for High-Temperature Super Conductor RF Filters

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The High Temperature Super Conducting (HTSC) radio frequency (RF) filters (as used, for example, in ground base stations for cellular phone systems) are passive devices. To operate properly, they must be cooled well below their transition temperature to super conducting stage (usually to 65–80 K). These HTSC RF filters are connected through a coaxial cable to an array of Low Noise Amplifiers (LNA), which are active devices and, therefore, induce a few hundreds mWatts of heat. On the other hand, the LNA array is connected by coaxial cable to a feedthrough of the vacuum chamber. This coaxial cable also contributes a few hundreds mWatts of heat load. The third source of heat load is the thermal radiation from the vacuum jacket wall to the cryogenically cooled surfaces. This portion of heat load is assessed as hundreds of mWatts as well. The signal-to-noise ratio of LNA devices is improved significantly when they are cooled down to a temperature of 90–110 K and their effectiveness reaches 99% at a temperature of 77 K. Traditionally, cooling of the system is achieved by placing both the HTSC RF filters and the LNA array device on the cold tip of a single-stage cryogenic cooler. Hence, both devices are cooled down to a temperature of 60–80 K, which is required by the manufacturers of HTSC RF filters. Because of the high level of heat loads induced by the LNA array, this method requires an extra cooling capacity from a cryogenic cooler. This increases power consumption, weight, and size and decreases its reliability. This paper describes a method of reducing the overall heat load. This method relies on the idea of maintaining the HTSC RF filters and the LNA arrays in different operational temperatures. The objective of this method is to provide a reduction in thermal losses, input power, weight, and size and to increase the reliability of the entire cryogenic cooler. The method allow for better ruggedising of the mechanical support for cooled electronic package of the LNA array plate.

KEY WORDS: Cryocooler; RF filter; superconductor; communication; cellular.

1. INTRODUCTION

The worldwide competition in the modern market of cryogenic coolers demands more reliable, light weight, compact, and efficient cost-saving products. One of the potential sources of improving such performances is matching the entire design of a cooler to a specific application. In this paper we discuss the matching of a Stirling linear cryocooler for cooling

HTSC RF filters for the cellular telephone ground base industry. Such a system allows for better filtering of RF signals received by an antenna and also improving the signal-to-noise ratio.

Powerful and sensitive antennas are required to receive the weak electromagnetic signals, which are remotely emitted by cellular phones and other communication devices. Essential electronic components used for this purpose are filters, which cut out noise, and amplifiers, which increase the signal level. A radiation shield is also helpful in cutting out unwanted incoming thermal radiation and in reducing heat load of the electronic components, thus reducing the overall heat load on the cooler.

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In practice, satisfactory results are obtained by using the superconducting filters matched with a low-noise amplifier (LNA) array. High temperature superconducting filters operate well when cooled down to a temperature of 65–80 K. The amplifier array and radiation shield also require cooling, although these components operate satisfactorily in the 90–110 K temperature range.

2. CURRENTLY USED APPLICATION

Present cooling devices use a single stage cryogenic cooler (Fig. 1), which is optimized to operate at a temperature of about 65 K in order to meet the demands of RF filter cooling. The amplifiers (4), RF filters (5), and radiation shield (6) are thermally connected to the same single source of cooling (2). Although these items are overcooled, they operate satisfactorily.

The disadvantages of such a design lies in the high power consumed by the cooler, and in its corresponding size, weight, and buying and running cost. As the working temperature of any refrigerator is lowered, the work required for transferring a given amount of heat increases. This is evident from the Carnot relationship:

$$W = Q \cdot \frac{T_1 - T_2}{T_2}$$

where W is the work required for extracting heat Q at a low temperature T_2 and rejecting it at a high temperature T_1 .

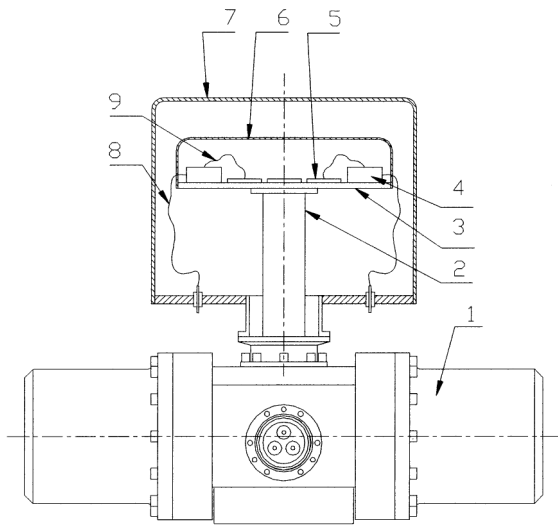


Fig. 1. Single stage cooler assembly.

A further disadvantage of overcooling the radiation shield and the amplifiers array is readily explained by the fact that these components contribute the major portion of the heat load. The amplifiers array is an active heat-generating device, and the radiation shield has a substantial size. Furthermore, during start up, the cooler is delayed in achieving the operational temperature required by the filters because of the necessity of additional heat extracting from the amplifiers array and radiation shield.

Therefore, the object of the RICOR's invention covered by a patent (pending) was to obviate the disadvantages of prior art coolers for RF antennas and to provide a new cooler, which requires less power to operate, has a lower cost, and has a longer life.

3. DESCRIPTION OF THE NOVEL SOLUTION

RICOR's invention achieves these objectives by providing a cryocooler for simultaneous cooling of RF filters and a LNA array to different specific cryogenic temperatures, which are sufficient for their operation. The cooler is a Stirling-cycle engine (Fig. 2), which consists of the double-piston linear compressor (1) and two-stage reciprocating expander (2). The RF filters (5) are mounted on the base plate (11), which is thermally coupled with the second-stage gas expansion chamber (10). RF filters are preferably of the high temperature superconducting type, and, therefore, suitable second-stage temperature is in the range of 65–80 K.

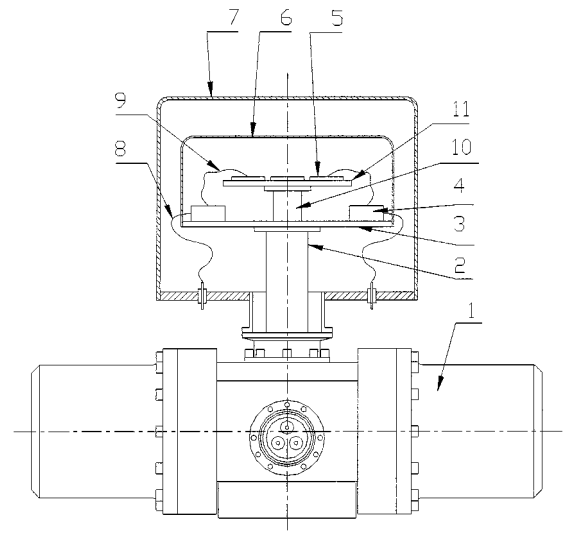


Fig. 2. Two-stage cooler assembly.

The LNA array (4) is mounted on the base plate (3), which is thermally coupled with the first-stage gas expansion chamber (2). Cooler's embodiment comprises a radiation shield (6), which is mounted in thermal coupling with the first-stage gas expansion chamber. It is cooled together with the LNA to the first-stage temperature of 90–110 K. The whole construction is placed in a vacuum envelope (7). Electrical connections of the RF filters, LNA array, and vacuum feedthrough are carried out by coaxial cables (8,9).

4. QUANTITATIVE ANALYSIS

Quantitative analysis of cooler performances was carried out by a computer simulation in order to com-

pare power consumption, life expectancy, and cost of both two-stage and single-stage cryocoolers.

For this purpose, two computer models were created, based on the same compressor unit and with different reciprocated expanders, namely, single-stage and two-stage.

“SAGE” object-oriented software was used for building the models and optimization. Schemes of single-stage and two-stage models are presented in Figs. 3 and 4.

Relevant parameters of these two expanders were simultaneously optimized in order to get minimal power consumption at the same total effective cooling capacity as the optimization carried out by SAGE's built-in optimizer. Table I presents the optimization highlights of the two cryocooler configurations.

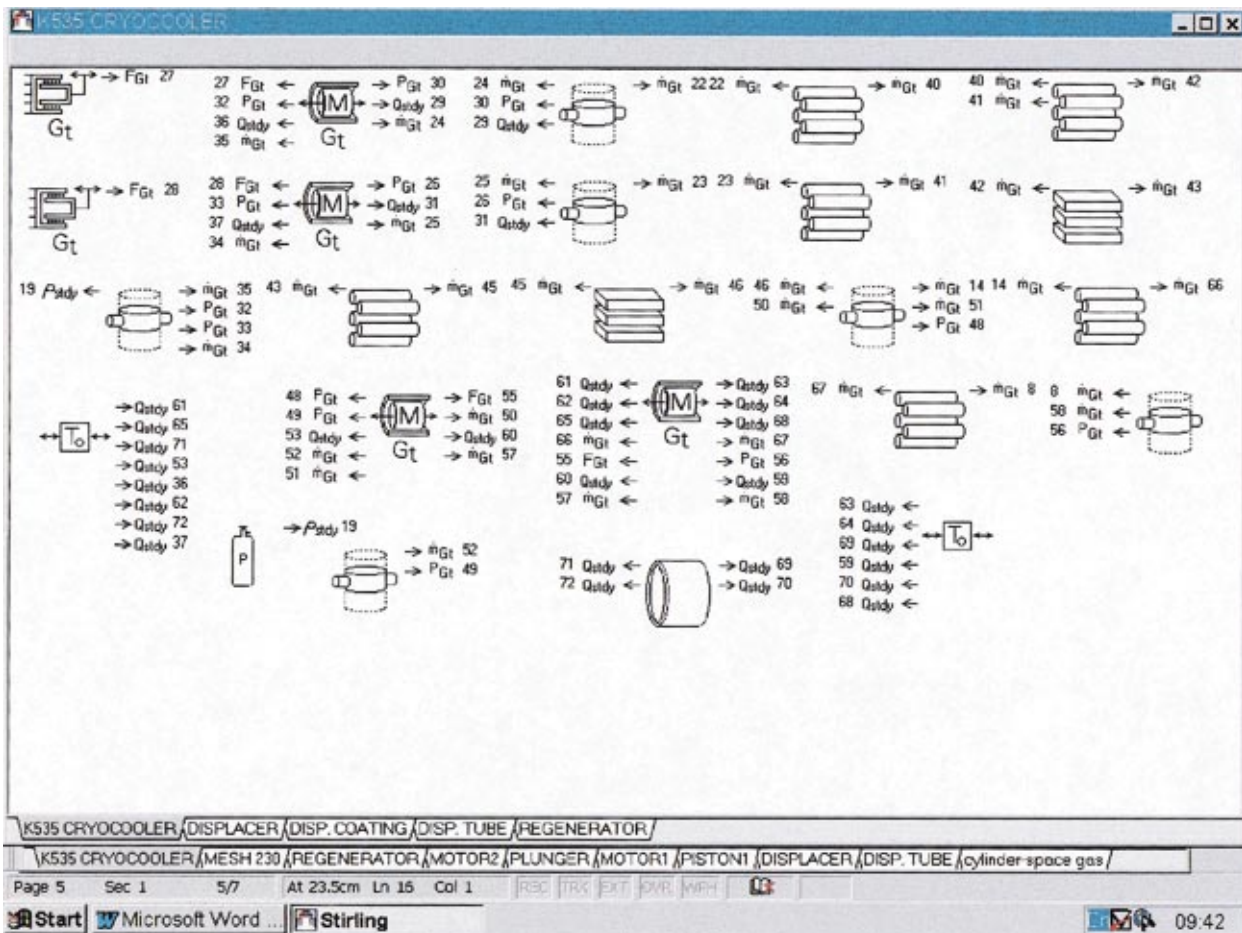


Fig. 3. “SAGE” model scheme of single-stage cryocooler.

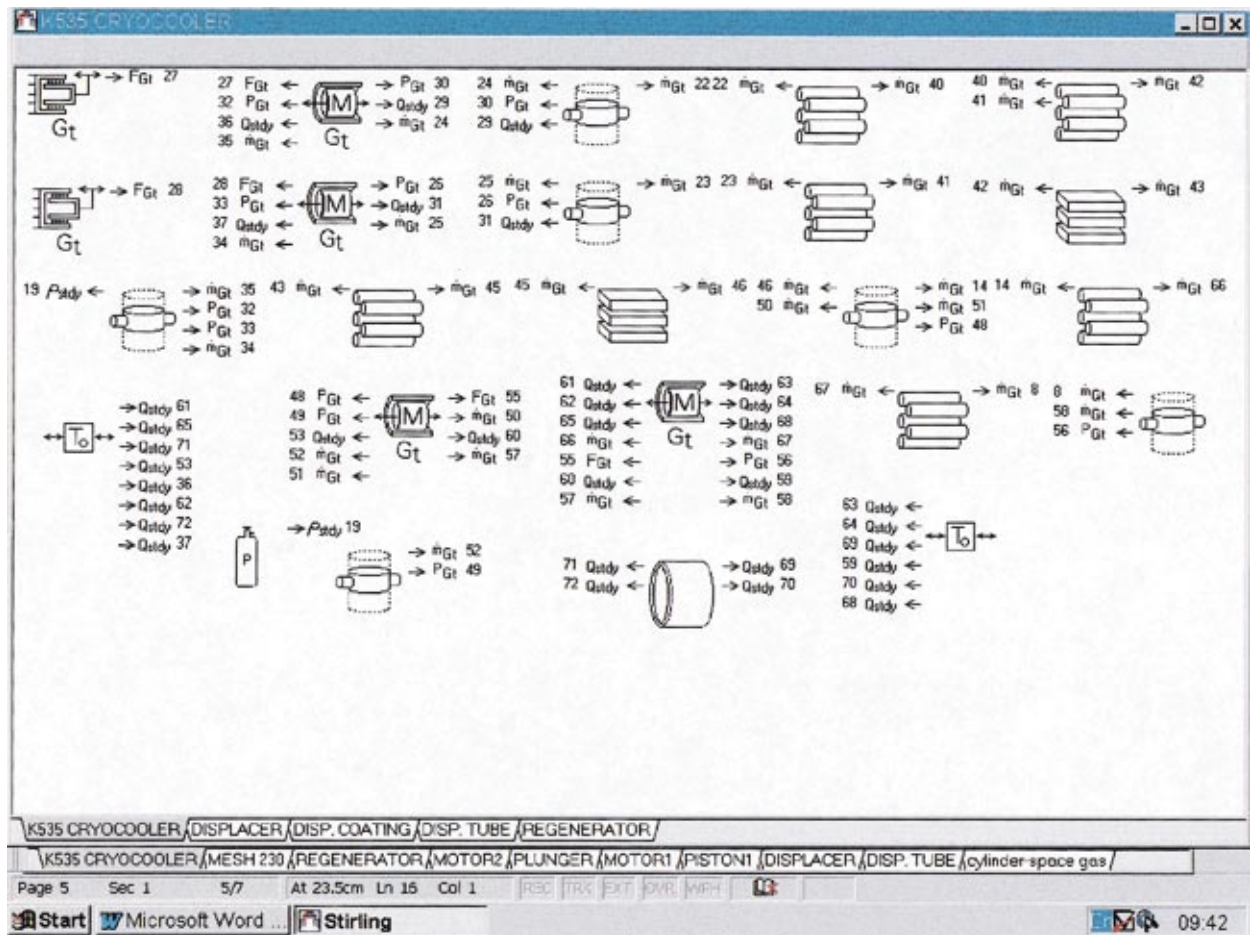


Fig. 4. “SAGE” model scheme of two-stage cryocooler.

Table I. Optimization Highlights

Parameters	Single-stage expander	Two-stage expander
Optimization objective	COP ^a maximize	Integral COP ^b maximize
		Regenerator length
	Regenerator length	(1st and 2nd stage)
	Regenerator diameter	Regenerator diameter
Optimized variables	Charge pressure	(1st and 2nd stage)
	Linear motor current	Charge pressure
		Linear motor current
Cold-tip temperature (K)	65	100 (1st) & 65 (2nd)
Goal cooling capacity (W)	3.5	3 (1st) & 0.5 (2nd)
Goal power consumption (W)	100 max	100 max
Goal cold-finger length (mm)	100 max	100 (1st + 2nd) max

^aCoefficient Of Performance = effective cooling capacity divided by electrical power consumption (%).

^bSum of 1st and 2nd stage effective cooling capacities divided by electrical power consumption (%).

Table II. Optimization Outputs

Parameters	Single-stage expander	Two-stage expander
COP (%)	2.9	4.9
Cooling capacity (W)	3.5	3.0 (1st) & 0.5 (2nd)
Power consumption (W)	120	72
Cold finger length (mm)	89	62 (1st) & 45 (2nd)

The other geometric, thermal, and dynamic parameters of cryocooler construction were the same during computer optimization for both of the configurations. The general output parameters after optimization are compared in Table II.

5. CONCLUSIONS

Predictiveness of the SAGE simulation modes had been proven during previous RICOR's developments. The single-stage linear twin-piston cryocooler (K535) was built by RICOR in accordance with the simulation model mentioned previously. These cooler

performances were satisfactorily matched with the optimization results.

As estimated by simulation, the presented new solution for cryocooler for HTSC RF filters application demonstrated the following benefits:

- Electrical power saving of about 35%.
- Decrease of heat produced by compressor by about 30%.
- Increase of cooler reliability.
- Increase of cooler life time.
- System simplification by lower requirements to heat dissipation.
- Operation of RF filters and LNA at their specified temperatures.
- RF filters and LNA array construction is more rigid as compared with the single-stage option.
- Potentially lower cost due to higher cooling power redundancy.

This novel design concept was patented by RICOR as a preferred construction for the specific needs of the HTSC RF filters application.